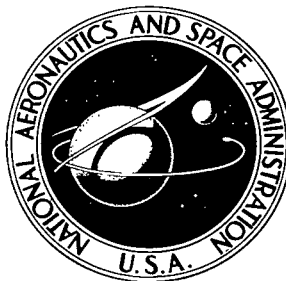NASA TECHNICAL NOTE

X-RAY OBSERVATIONS OF FLOW PATTERNS IN A MERCURY BOILER

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16. Abstract

X-ray techniques were used to observe two-phase flow patterns in a metallic, forced-flow mercury boiler. Helically swaged grooves in the boiler tube were used to swirl the liquid phase. This produced an essentially helical streamlet of liquid flowing in contact with the boiler wall. The observed flow pattern could be generally characterized as stratified and in agreement with the pattern predicted by previous flow pattern mapping studies. X-ray observations were made under both stable and metastable flow conditions.

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SUMMARY

Flow patterns in an electrically heated, forced-flow mercury boiler were studied with a high-resolution X-ray image system. The boiler consisted of a thin-wall metallic tube with a swaged helical groove along its length. This groove was a swirling device that helped separate the liquid phase into an essentially helical streamlet flowing in contact with the boiler wall. There were long periods of stable operation during which X-ray observations showed good separation of the liquid phase and no detectable liquid carryover into the superheater.

An attempt was made to explain the observed flow patterns in terms of patterns predicted by previous adiabatic studies made with other fluids. There were close similarities between the observed and predicted patterns, but the observed patterns depended strongly on the intimate liquid-to-boiler-wall contact produced by the helical motion of the mercury. Because of the high surface tension of mercury, the stratified flow with good phase separation that was observed cannot be readily reproduced in straight-tube boilers. Prior X-ray observations of straight-tube prototype boilers indicated that, with mercury, phase separation (swirling) devices are needed.

X-ray observations were also made during metastable intervals when there were flow and pressure oscillations and excursions. In these instances, the X-ray aided in identifying phenomena that appeared to trigger and sustain metastable conditions in the boiler. Using flow pattern and other observations, it was concluded that metastable oscillations were promoted by nucleation effects in the boiler inlet region.

INTRODUCTION

The advent of advanced nuclear space power systems has generated investigative effort for improvement and development of power conversion devices based on two-phase flow of mercury and alkali metals. Two topics of interest have therefore been flow stability and flow pattern control in liquid-metal boilers. In particular, flow pattern con-

trol efforts have been concerned with the prevention of undesirable liquid entrainment in vapor flows.

An X-ray method for observing flow patterns was developed as a part of a forced-flow mercury-loop design. The loop was primarily an instrument for investigating mercury corrosion under two-phase flow conditions.

Prior to the construction of the loop described herein, several prototypes were tested. Each of these also incorporated the X-ray image system for flow observation. The first prototypes used straight cylindrical boiler tubes. The problems of producing stable boiling and preventing liquid entrainment (carryover) with mercury became apparent at once. Because of surface tension and dewetting effects, there is a tendency for liquid droplets and slugs of mercury to form and separate from the mainstream. These can be carried downstream by high-velocity vapor. Under this condition, boiler and superheater performances degenerate, and stable operation with high-quality vapor cannot be attained. Therefore, phase separation devices are useful in forced-flow mercury boilers to promote sustained intimate wall contact for inducing wetting and, hence, improving stability and performance.

Recently developed mercury boilers contain swirling devices that promote phase separation, increase boiling stability, and reduce the tendency for slug formation (refs. 1 to 4). Because of the wide use of swirling devices for flow pattern control, there is interest in observing flow conditions produced with swirlers. A number of investigators have studied actual and simulated liquid-metal flow under both adiabatic and diabatic conditions (refs. 3, 5, and 6). An opportunity for direct observation of actual high-temperature flow patterns in a mercury boiler was afforded by the corrosion loop. By use of an X-ray photographic system coupled with an electronic image amplifier, the mercury loop provided clearer flow pattern observations than heretofore available, although X-ray methods have been used before (refs. 7 to 9). A motion-picture film supplement that shows the flow patterns observed in this investigation has been prepared and is available on loan. A request card and a description of this film are included at the back of the report.

The purpose of this report is to describe the observed flow patterns obtained under both stable and metastable conditions. Included herein are conclusions concerning methods for phase separation in mercury boilers and causes of metastable flow based on X-ray observations. The post-test corrosion results that were relevant to flow pattern phenomena are also described. A full account of the corrosion results is given in reference 10.

APPARATUS

The mercury loop was a tubular flow circuit having the following major components:
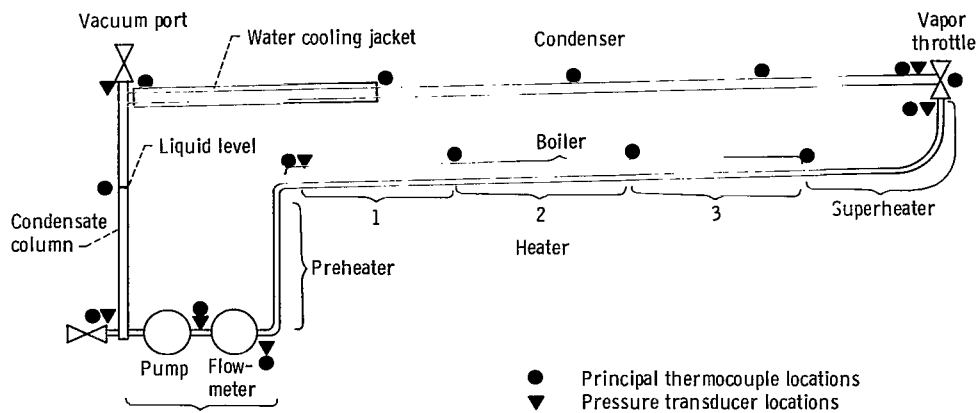
Figure 1. - Two-phase mercury loop.

preheater, boiler, superheater, vapor throttle, condenser, condensate column, electrodynamic mercury pump, and flowmeter. The arrangement of the loop components is shown in figure 1. The loop material was a cobalt-base alloy, HS-25.

With the exception of the pump cell and flowmeter, all major parts of the loop were arranged in a vertical plane (figs. 2 to 4). The purpose of this layout was to permit con-

Figure 2. - Front view of mercury loop.

Figure 3. - Condensate end of mercury loop.

Figure 4. - Back view of mercury corrosion loop.

Figure 5. - X-ray traverse and image system.

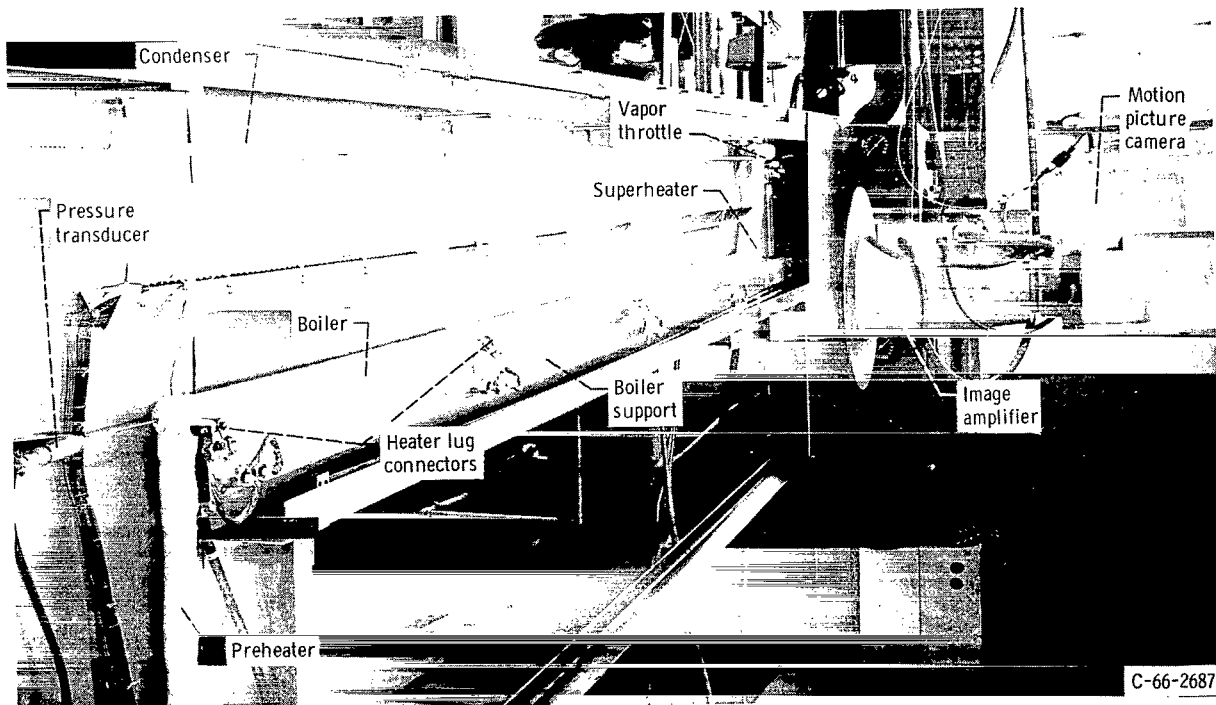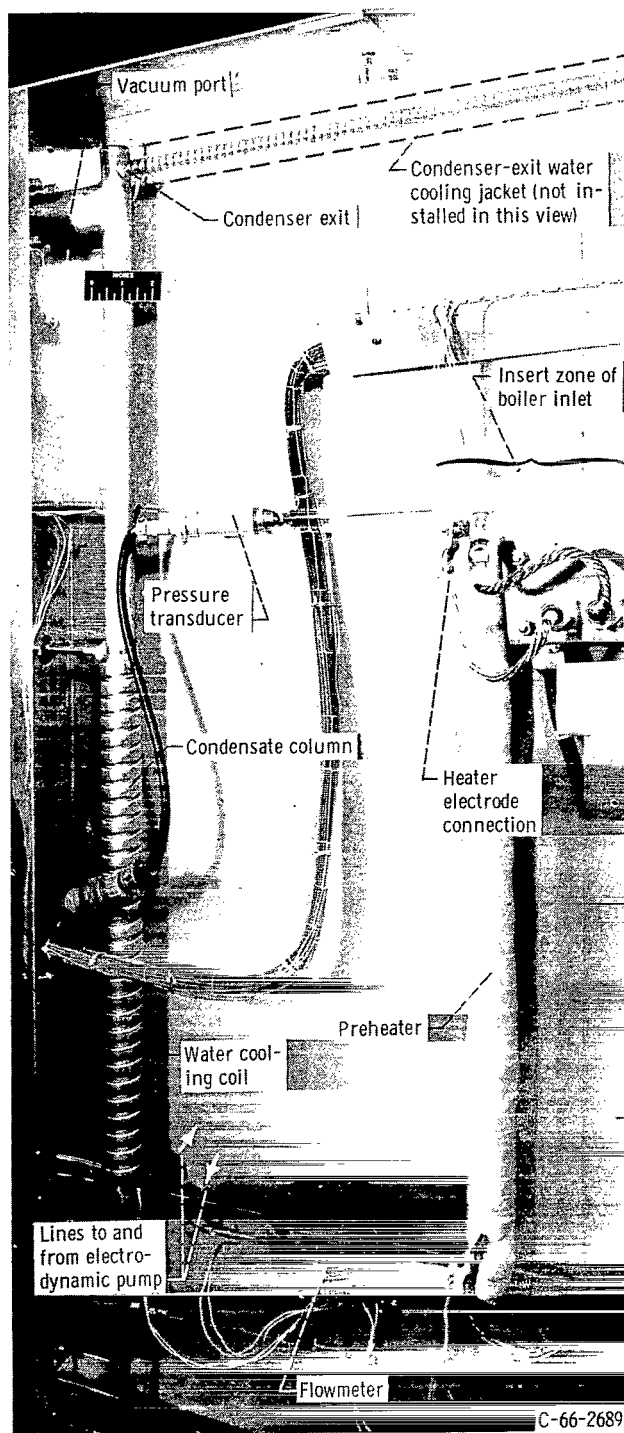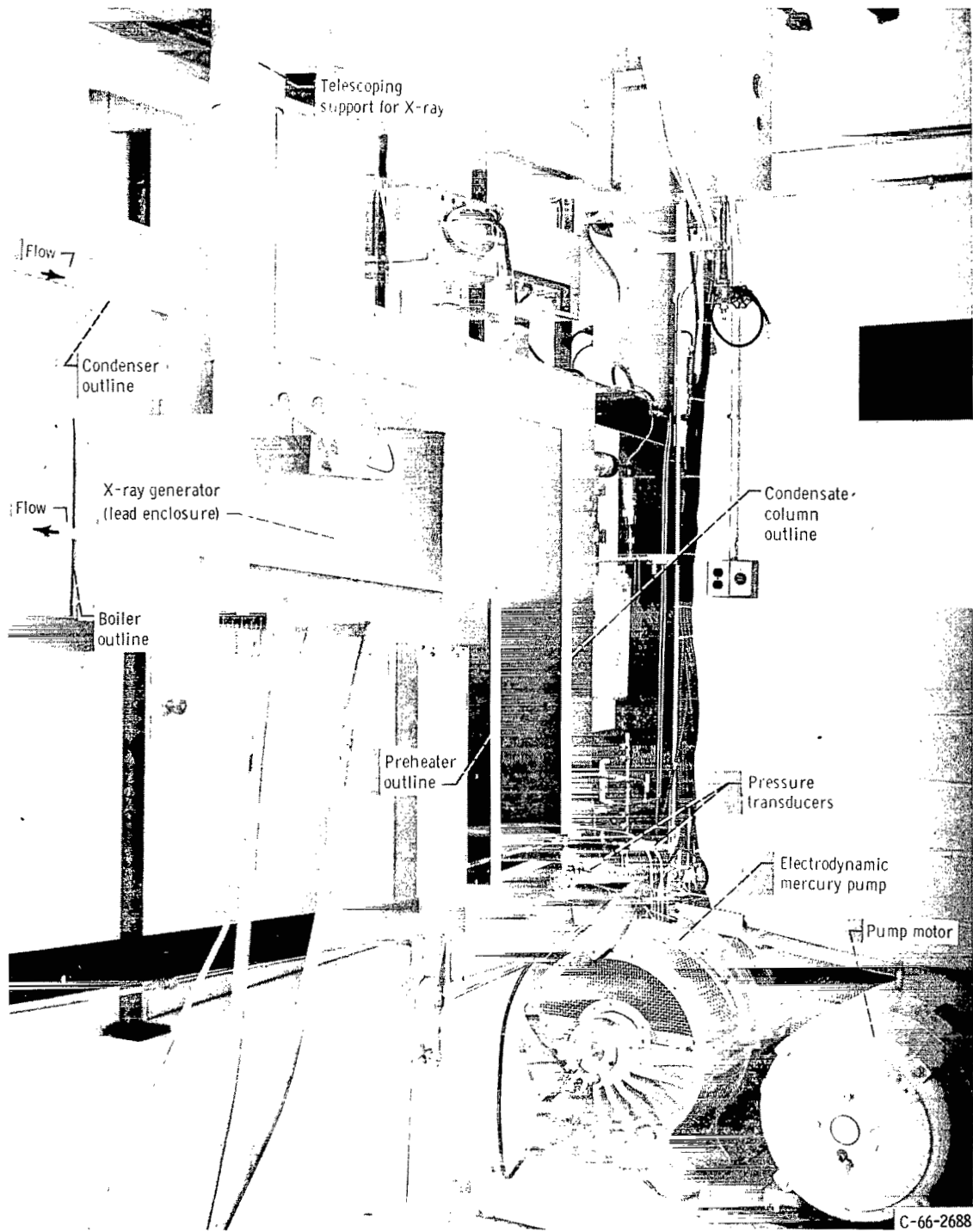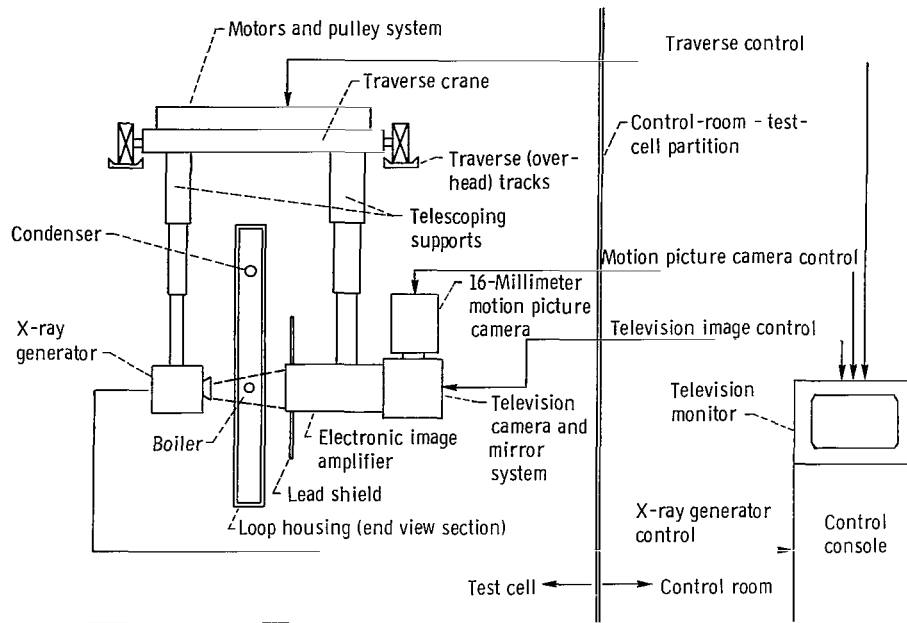venient X-ray viewing of boiling and condensing flow patterns. The X-ray apparatus could scan the loop from the boiler inlet through the condenser exit.

As indicated in figure 5, a closed-circuit television monitor was used with the X-ray system. A remote control arrangement was used to scan and select views of the loop. The television monitor served as a guide. The X-ray system included an electronic image amplifier and a motion picture attachment.

Details of Construction

The details of the boiler, superheater, and vapor throttle construction are described in the following paragraphs. In designing these components, particular attention was paid to making them easy to view with the X-ray system.

The boiler-superheater component consisted of a single length of tube with a 1/4-inch (0.63-cm) outside diameter and a 0.020-inch (0.05-cm) wall thickness. The boiler-superheater tube was 115 inches (292 cm) long and had a swaged helical groove along its entire length. The first 90 inches (228 cm) constituted the boiler. The super-heater was a curved section beginning a few inches beyond the boiler outlet (figs. 1 and 2).

Typical helically swaged boiler sections are shown in figure 6. The pitch of the helix was 1/8 inch (0.32 cm), and the inside diameter of the groove was slightly greater

6
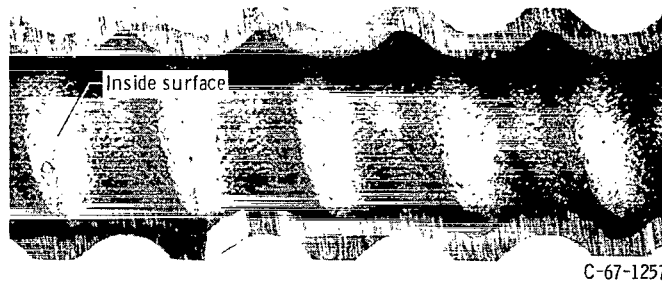
(a) Half-section of deep-swaged helical groove used near boiler inlet.
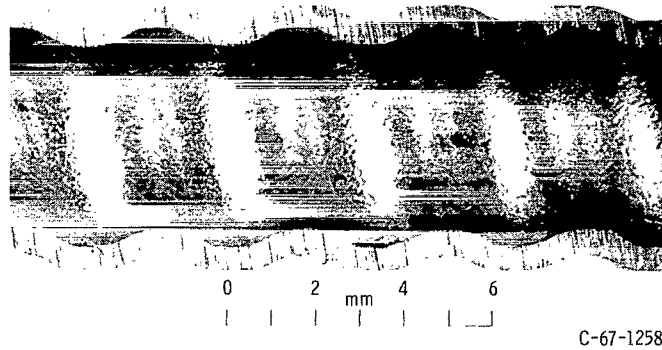
(b) Half-section of shallow-swaged helical groove used downstream of boiler
    inlet and in superheater.

Figure 6. – Helically swaged boiler tube.

than 1/8 inch (0.32 cm). After swaging, the depth of the groove in the first 12 inches
(31 cm) of the boiler was about 0.03 inch (0.08 cm), and thereafter the depth of the
groove was about 0.02 inch (0.05 cm). This change in depth and character of the groove
is seen by comparing figures 6(b) and (c), and it may have been a factor affecting the
flow pattern observed in this region.

The inlet of the boiler contained a 6-inch- (15-cm-) long, 1/8-inch- (0.32-cm-) di-
ameter cylindrical insert. The insert fit tightly inside the swaged boiler tube (fig. 7) so
that a helical channel was formed.

The boiler had three independently heated zones. The preheater and superheater
were also independently heated. Electrical resistance heater elements were used to heat
each of the five separately heated zones from the preheater through the superheater
(fig. 1). Each heater element was made of strips of a nickel-chromium alloy ribbon.
Each strip was formed into a half cylinder, and the half cylinders were clamped around
the loop tube, as shown in figure 8. Alumina spacer rings were used to separate these
tubular heater elements from the loop tube. Several layers of thermal insulation of
quartz fiber and ceramic were applied over the heaters. Additional layers of quartz-
fiber blanket insulation were added over those shown in figure 8.
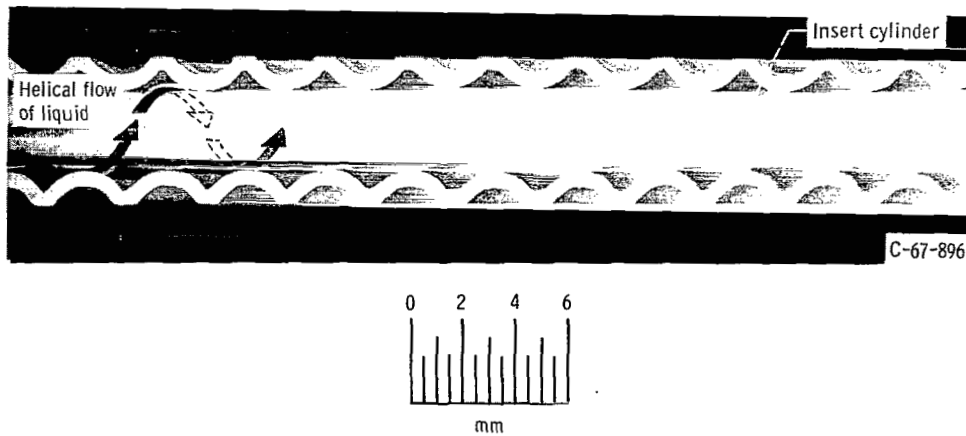
Figure 7. - Portion of boiler insert zone with front half of helically swaged boiler cut away.
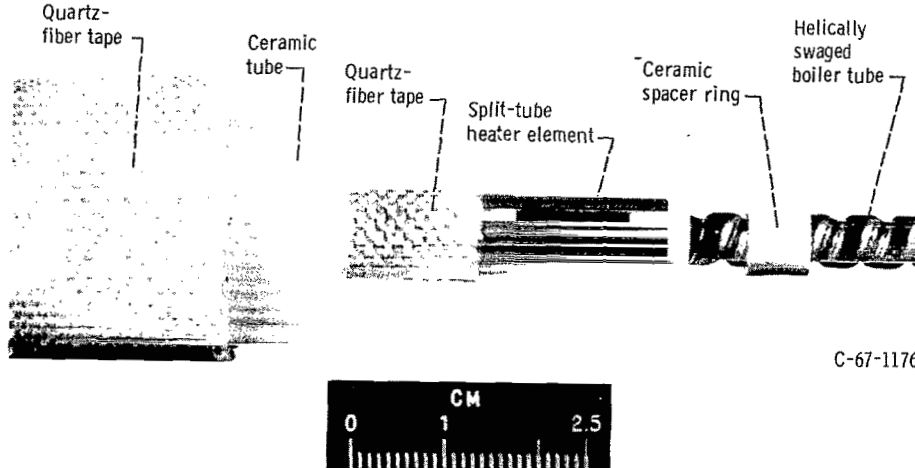
Figure 8. - Cutaway mockup of insulation and electric heater element used to heat loop boiler-superheater.

The vapor throttle was a metallic, weld-sealed needle valve. The inlet tube extended into the expansion chamber so that the throttling orifice was surrounded with an expansion space (fig. 9(a)). As seen in figure 9(b), the throttle configuration permitted an X-ray silhouette of inner parts surrounding the orifice. Sufficiently dense fluids (i.e., liquid carryover and droplets) could be observed flowing through the throttle. The throttle was thoroughly covered with a thick layer of quartz-fiber insulation and was heated only

8
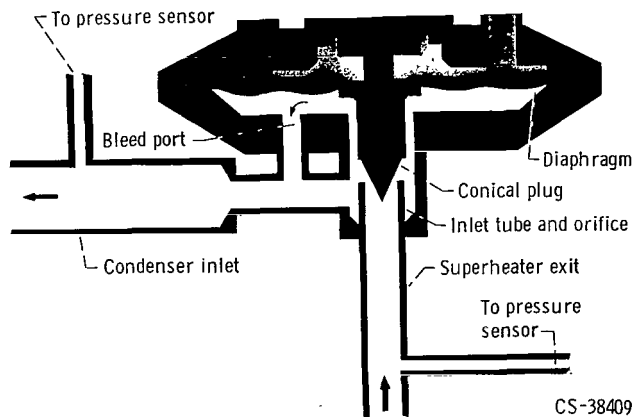
(a) Cross section of vapor throttle showing internal passages.
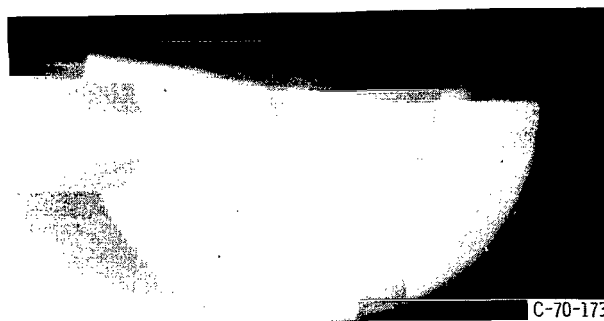
(b) X-ray silhouette of vapor passage through vapor throttle.

Figure 9. - Vapor throttle for experimental mercury loop.

by the mercury entering from the superheater. Some of the conclusions herein relative to metastable performance depend on X-ray observations of the throttle.

Instrumentation

Thermocouples were attached to the outside surface of the loop tubing at regular intervals. From the preheater through the superheater, the thermocouples were attached to the tube in the essentially adiabatic spaces between heaters. The thermocouples were spot welded to the tube and covered with quartz-fiber insulation. The locations of the more important thermocouples are identified in figure 1. The principal thermocouples on the boiler, superheater, and vapor throttle were platinum - platinum-13-percent rhodium. The rest were Chromel-Alumel thermocouples, or iron-constantan thermocouples. Additional thermocouples were included for heater power control.

Pressure measurements were obtained with strain-gage-type pressure transducers. The transducers were connected to the loop with small-bore tubing. Pressure was

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transmitted from the loop to the transducer diaphragm by liquid mercury. The previously mentioned insert in the boiler inlet was an extension of one of the pressure transmission tubes and was used to measure the boiler inlet pressure. Pressure tap locations are indicated in figure 1.

At the condenser exit (over the condensate column), the pressure was in the microtorr range and, therefore, was sensed by a vacuum gage. This measurement was made intermittently by opening the vacuum port indicated in figures 1 and 3.

The flowmeter consisted of 12 feet (360 cm) of tubing with a 1/16-inch (0.16-cm) inside diameter. The mercury flow rate was determined by the pressure difference between the flowmeter inlet and exit. The relation between pressure drop in the flowmeter tube and flow rate was obtained by direct calibration.

OPERATING CONDITIONS

The operating conditions in the mercury loop were set to meet the experimental requirements of the corrosion experiment for which the loop was designed. A prerequisite condition was that the mercury wet the boiler surface to a sufficient degree. This would help to produce good corrosion results as well as better heat transfer. Measures were therefore taken to induce wetting by the procedure described in appendix A. There was no way to determine if optimum wetting had been attained in the boiler, but there were indications that the conditioning procedure substantially improved the relative degree of wetting.

The loop operated semiautomatically with proportional feedback control for a total of 1147 hours. Periodic manual adjustments were required to compensate for drifts from normal conditions. After steady conditions were established, they usually persisted without a need for manual adjustments for intervals of 10 to 25 hours under automatic control. These stable conditions were sometimes interrupted because of line voltage perturbations.

Loop control was based on the wall temperatures along the preheater and boiler-superheater. The desired temperature levels and permitted temperature ranges at the end of each of the five heated zones were preset. When any disturbance occurred in the preset temperature pattern, a compensating change in the heater power levels automatically readjusted the heat input. The boiler inlet pressure and vapor throttle opening remained fixed so that all corrections were made solely through boiler power adjustments.

The normal operating conditions are summarized in table I. The normal mercury flow rate was about 78 pounds per hour (9.8×10^{-3} kg/sec). Corresponding to this flow rate was a liquid velocity of about 3 feet per second (90 cm/sec) in the liquid-filled helical channel around the insert at the boiler inlet. The downstream half of the insert zone

TABLE I. - MERCURY LOOP OPERATING CONDITIONS[a]

Mass flow rate, lb/hr; kg/sec . . . . $78; 9.8 \times 10^{-3}$

Flowmeter pressure drop, psid; N/m^2 . . . . $26; 1.7 \times 10^5$

Preheater inlet temperature, °F; °C 110; 45

Boiler
    Inlet pressure, psia; N/m^2 abs . . . . $300; 2.1 \times 10^6$
    Inlet temperature, °F; °C 950; 520
    Peak insert zone temperature, °F; °C 1075; 583
    Insert zone pressure, psia; N/m^2 abs . . . . $270; 1.9 \times 10^6$
    Insert zone pressure drop, psid; N/m^2 . . . . $25; 1.7 \times 10^5$
    Exit temperature, °F; °C 1040; 563
    Average heat flux, Btu/(hr)(ft^2); W/m^2 . . . . $2 \times 10^4; 6 \times 10^4$

Superheater
    Exit pressure, psia; N/m^2 abs . . . . $240; 1.6 \times 10^6$
    Exit temperature, °F; °C 1350; 730
    Average heat flux, Btu/(hr)(ft^2); W/m^2 . . . . $9 \times 10^3; 3 \times 10^4$

Condenser
    Inlet pressure, psia; N/m^2 abs . . . . $12; 8.3 \times 10^4$
    Inlet temperature, °F; °C 1100; 595
    Exit pressure,[b] psia; N/m^2 abs . . . . ~0
    Exit temperature,[c] °F; °C 80; 25

Pump
    Inlet pressure,[d] psia; N/m^2 abs . . . . $12; 8.3 \times 10^4$
    Developed pressure,[e] psid; N/m^2 . . . . $315; 2.2 \times 10^6$

[a]All values are approximate: pressures are rounded to two significant figures except for pump developed pressure. Temperatures are rounded to three significant figures except for insert zone peak temperature.

[b]Condenser exit pressure was in $\mu torr$ range.

[c]Last 2 ft (62 cm) of condenser were cooled by water jacket and upstream of this, condenser was cooled by natural air convection and radiation.

[d]Pump inlet pressure was produced by "static" head of mercury in condensate column (see fig. 1).

[e]Pump developed pressure was independent of flow rate in flow rate range of loop experiment.

had concurrent liquid and vapor flow. The tangential velocity of the liquid phase near the end of the insert was estimated to be about 8 feet per second (240 cm/sec).

METASTABLE FLUCTUATIONS

During the latter part of the 1147-hour test, there were more frequent intervals when the conditions in the loop became metastable. During the metastable intervals, there were cyclic flow, pressure, and temperature oscillations and excursions. Typical

Flow rate,
lb/hr (kg/sec)

83 (.011) ┐ ┌ 98 (.012)
67 (0.008) │ │ │ 109 (.014)

60

← Flowmeter pressure drop

Boiler exit tem-
perature →

30

Boiler satura-
tion pressure

Time, min

0   50   100   150   200   250   300
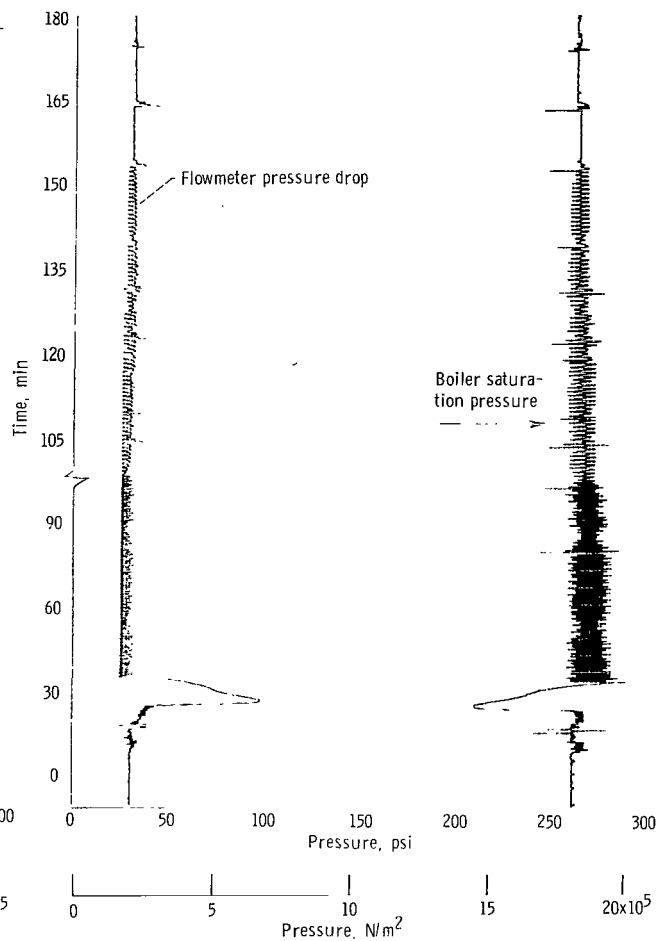   Pressure, psi

0   5   10   15   20x10⁵
              Pressure, N/m²

0   200   400   600   800   1000   1200
              Temperature, °F

0   100   200   300   400   500   600
           Temperature, °C
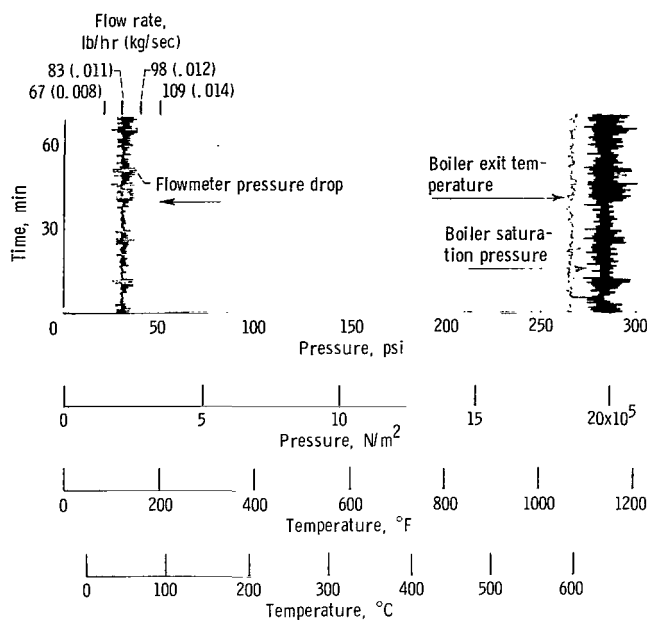
(a) Typical covariation of flow rate and boiler saturation pressure and tem-
    perature during oscillations.

320

290   Flowmeter pressure drop ←

260   Boiler satura-
                                             tion pressure →

230

Time, min

120

90

60

30

0

0   50   100   150   200   250   300
              Pressure, psi

0   5   10   15   20x10⁵
              Pressure, N/m²
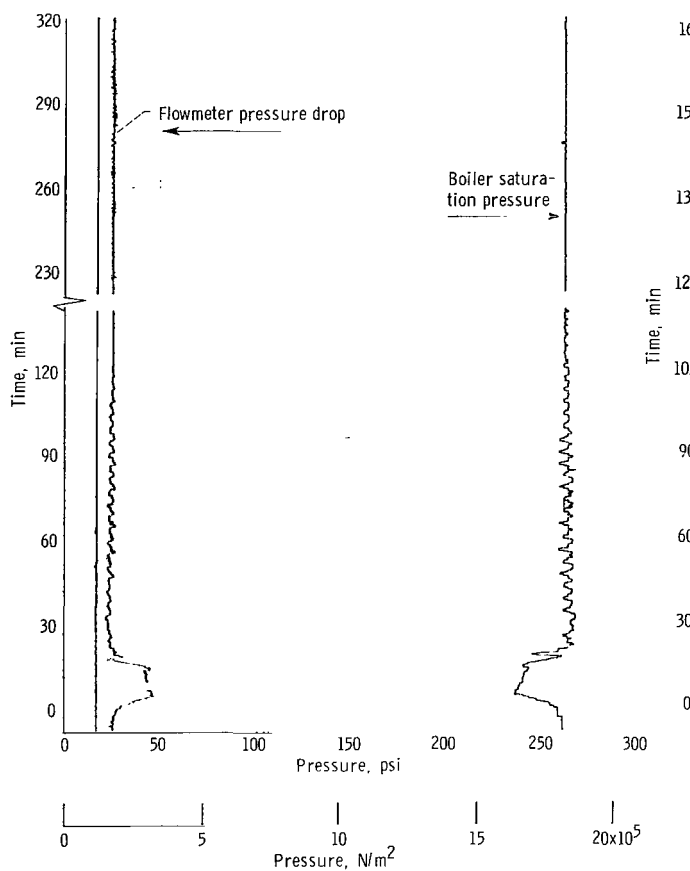
(b) Typical minor flow and pressure excursions and oscillations under self-
    dampening conditions.

180

165

150   Flowmeter pressure drop

135

120   Boiler satura-
                                             tion pressure →

Time, min

105

90

60

30

0

0   50   100   150   200   250   300
              Pressure, psi

0   5   10   15   20x10⁵
              Pressure, N/m²

(c) Typical major flow and pressure excursions involving high frequency
    oscillations.

Figure 10. - Covariation of flow rate, pressure, and temperature during intervals involving oscillations and excursions.

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traces of flow, pressure, and temperature oscillations and excursions that occurred during the metastable intervals are presented in figure 10. Usually, the amplitudes were small, and the normal operating conditions constituted the mean about which the deviations ranged.

Figure 10(a) typifies the flow rate, pressure, and temperature oscillations that occurred during some of the metastable intervals. During these intervals, the pump-developed pressure and pump-outlet pressure were constant and showed no tendency to oscillate or drift. The type of metastable condition represented by figure 10(a) usually prevailed for several hours and sometimes for a period of 10 hours during times when the loop was unattended and manual adjustments could not be made. As shown in figure 10(a), the flow rate varied about 14 pounds per hour $(17 \times 10^{-4}$ kg/sec), boiler saturation pressure varied about 25 psi $(1.7 \times 10^{5}$ N/m^2), and saturation temperature varied about 40° F $(22^{\circ}$ C). This type of condition usually required slight manual control adjustments to dampen and eliminate the oscillations. The most useful adjustment was to change the temperature level and gradient near the insert zone.

A typical minor metastable excursion is represented in figure 10(b). These excursions occurred after the loop had been operating in a normal steady mode for long intervals of the order of tens of hours. After the excursion in saturation pressure and flow rate (bottom of fig. 10(b)), the loop oscillated for about $1\frac{1}{2}$ hours and then automatically returned to normal. The type of pattern shown in figure 10(b) sometimes repeated itself five to six times during an interval of 24 hours.

A more pronounced excursion is represented in figure 10(c). This type of excursion was associated with a marked drift in the mean flow rate and mean saturation pressure. The particular pattern in figure 10(c) repeated approximately every 5 hours during an interval of 20 hours. Each time the excursion occurred, it was followed by oscillations that dampened automatically. During the dampening, the mean flow rate and saturation pressure drifted back to their previously set values. The flow and pressure traces were then quiescent until the next excursion. After adjustments were made to eliminate the pressure and flow drifts, the excursions ceased. The manual adjustments were increasingly difficult to make successfully as the test progressed and corrosive attack and mass transfer increased.

FLOW PATTERN OBSERVATIONS

The normal operating conditions for the loop are given in table I and are illustrated in figure 11. Also included in this figure are abbreviated descriptions of the two-phase flow patterns in the boiler, superheater, and condenser. These flow patterns were observed by means of the X-ray image system. A detailed description is given hereinafter
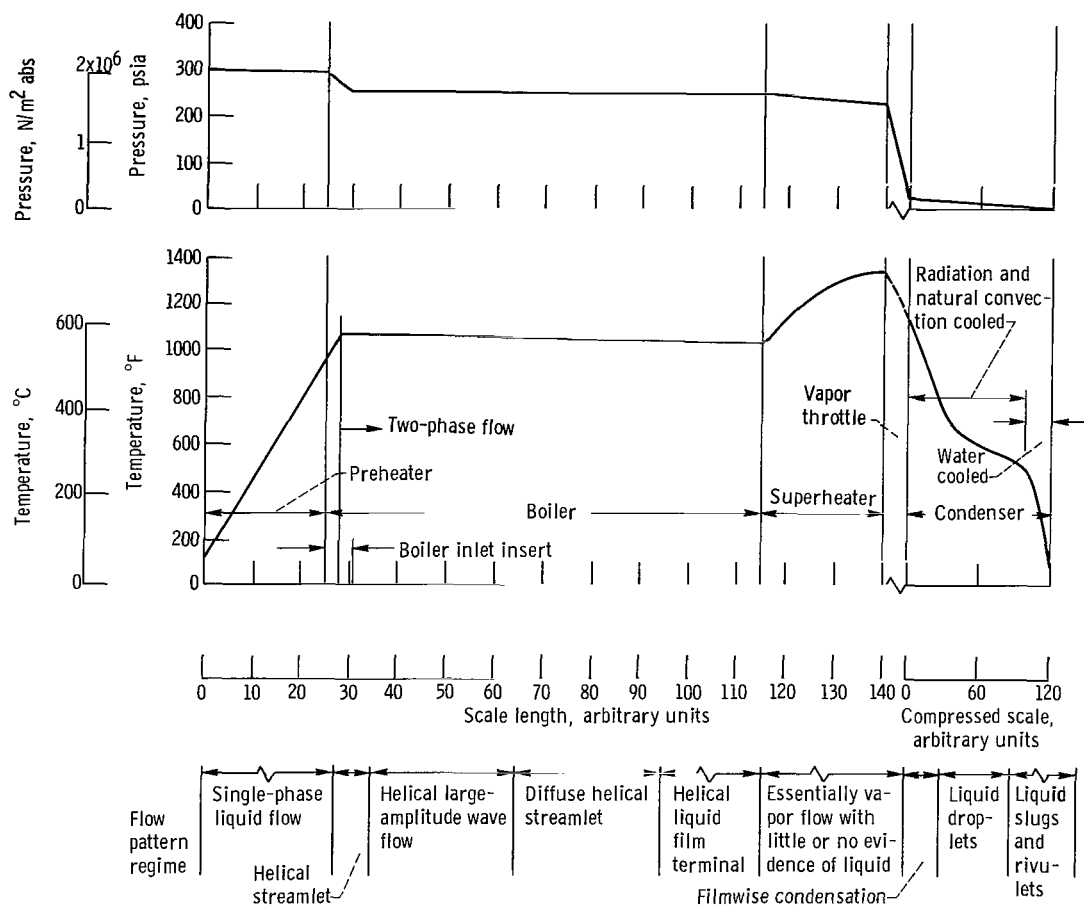
Figure 11. - Pressure and temperature profiles along loop and brief description of observed flow pattern regimes.

of the flow patterns observed in the boiler, superheater, and vapor throttle.

At the end of the corrosion test for which the loop was designed, the loop was dismantled. The preheater, boiler, superheater, vapor throttle, and condenser were sectioned and metallurgically examined. Corrosive attack and corrosion product deposits on the boiler wall were studied. The corrosion results of this loop are reported in reference 10. A motion-picture supplement (C-265) has been prepared to illustrate the flow patterns that were recorded with the X-ray image system. The motion pictures show details that are not readily reproduced by the half-tone photographs in this report.

The flow patterns are described in terms of the mercury liquid phase, which was opaque to X-rays. Droplets slightly less than 1/32 inch (1.2 mm) in diameter could be detected. Dispersed flow of a fine mist of mercury would have escaped detection. A film of mercury thicker than about 10^{-3} inch (2.5×10^{-3} cm), with the film front (edge) moving relative to the boiler-superheater wall, could be discerned. In the superheater, high-quality saturated vapor could not be differentiated from dry superheated vapor.

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Only the most visible and, hence, the densest part of the liquid stream is described. The description is therefore essentially of the bulk liquid flow, that is, flow of liquid having a thickness or diameter detectable by the X-ray technique used. This description should not be construed as excluding a thin liquid film that covered the boiler surface irrespectively of the bulk stream motion. This type of film-like coverage was inferrable after the loop was sectioned and examined for surface deposits and attack patterns.

Boiler-Superheater Flow Patterns

An X-ray scan from the boiler inlet through the superheater revealed variations in the liquid flow pattern. For example, the boiler could be divided into four parts, each having a characteristic pattern as summarized in figure 11. There was no strong demarcation zone between the flow pattern regimes, and the divisions in figure 11 are therefore somewhat arbitrary. In general, the liquid phase flowed as a separate streamlet and appeared to be in full contact with the wall except for undetected suspension of droplets or mist flow.

Helical streamlet. - The liquid mercury entering the boiler was constrained to flow
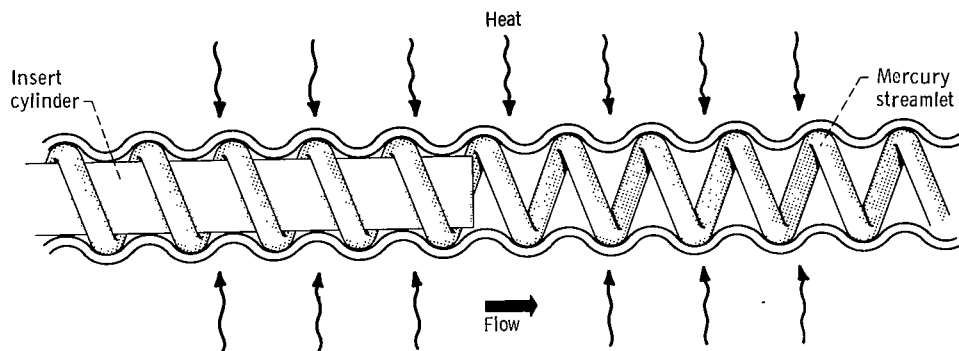
Figure 12. - Representation of helical liquid mercury streamlet in boiler insert zone.

in a helical path around the insert. The inception of boiling occurred about halfway along the insert. Thereafter, because of centrifugal forces, the liquid streamlet flowed circumferentially in the helically swaged groove of the boiler wall. This helical streamlet persisted past the end of the insert, as indicated schematically in figure 12. Figure 13 shows X-ray images of the helical streamlet at different positions near the insert.

The streamlet was sharply defined and highly stable in this part of the boiler.
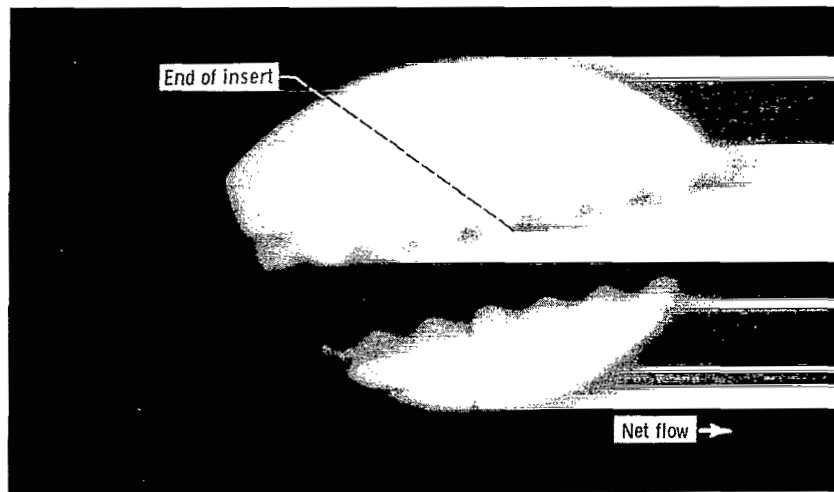
(a) Helical mercury streamlet at end of insert.

C-70-174
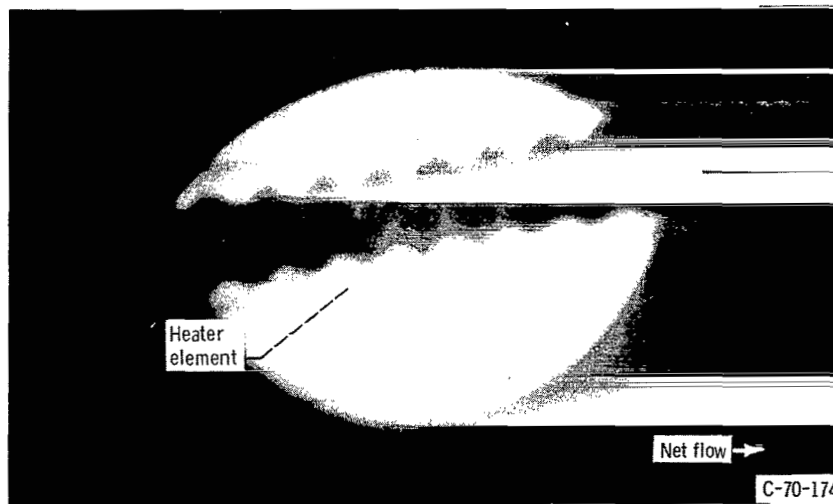
(b) - Helical mercury streamlet 2 inches (5.08 cm) downstream of insert end.

Figure 13. - X-ray images of helical flow pattern in boiler inlet zone.

There was no evidence of or tendency for the streamlet to break or overflow the groove. Because of the fairly high velocity, it was not easy to tell if the streamlet was continuous or contained a train of gaps that moved with the stream; however, the streamlet appeared essentially continuous. The vapor phase flowed axially (possibly with some vortex motion) through the open core of the boiler tube. The sharply defined helical streamlet began to change about 12 inches (31 cm) from the boiler inlet. This change in flow pattern appeared to coincide with the slight change in groove depth described previously in the section Details of Construction.

Helical large-amplitude wave flow. - As indicated in figure 11, a second characteristic flow pattern appeared about 12 inches (31 cm) downstream of the boiler inlet. This

second pattern persisted to a point about 40 inches (100 cm) from the boiler inlet.

In the second flow pattern regime, the liquid streamlet still flowed essentially helically in the grooves, but it consisted of a succession of large-amplitude waves. This was the only regime where the continuity of the bulk stream appeared broken by a succession of gaps. These gaps appeared at the beginning of this regime. Also, there was slight intermittent axial motion of mercury along the bottom of the boiler tube at the start of this regime. But generally, the liquid appeared to flow within the helical groove under the influence of centrifugal forces. At the end of this regime, the liquid phase again formed a continuous helical streamlet.

Diffuse helical streamlet. - The third flow pattern regime extended from about 40 to 70 inches (100 to 180 cm) downstream of the boiler inlet, as indicated in figure 11. In this regime, the liquid flowed in an apparently continuous, smooth helical streamlet. Compared with the well-defined streamlet near the insert, this streamlet was rather diffuse; that is, its bounds were fuzzy. As the liquid progressed farther along the boiler in this regime, the streamlet tended to spread axially in the groove. It appeared that the liquid was not confined to the deepest part of the groove but tended toward the crest. Here, the thickness of the bulk of the streamlet diminished markedly in the downstream direction because of evaporation. The drawing of figure 14 shows the diffuse helical streamlet regime.
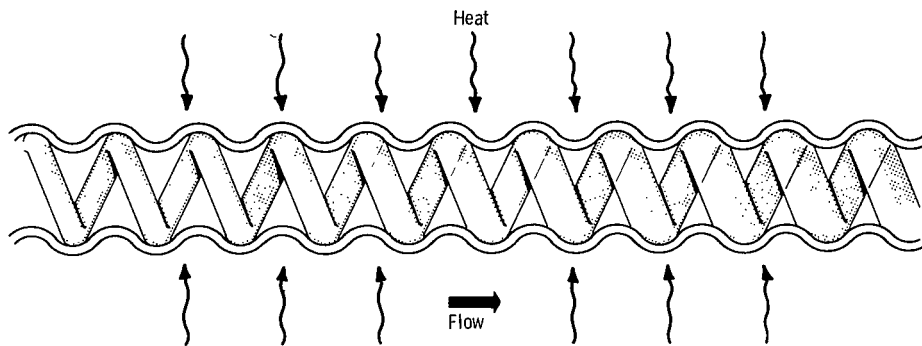
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Figure 14. - Representation of bulk of liquid flow in region of boiler in which diffuse helical streamlet existed (illustrated is general nature of bulk liquid flow pattern, showing axial spreading in downstream direction).

At fairly regular intervals, the helical pattern at the end of this regime exhibited a "wave train" effect, which suggested a train of helically moving waves superimposed on the main pattern. The time interval between successive waves varied from fractions of a minute to tens of minutes.

Liquid film terminal. - The last boiler regime was the locus where "wet wall" boil-

ing ended and essentially "dry wall" began. The liquid film terminal was not strictly a separate flow regime. Instead, it was a locus where observations revealed a thinning of the bulk liquid streamlet into a uniform film covering the boiler wall. This evidence of rather uniform film coverage was confirmed by the corrosion product deposit pattern found on post-test examination of the boiler.

The locus of the liquid film terminal was from about 70 to over 90 inches (180 to 230 cm) downstream of the boiler inlet; that is, according to the X-ray observations, this regime ended near the boiler exit (all visual traces of the liquid phase vanished as the liquid film progressively thinned).

Superheater flow pattern. - From the superheater inlet to exit, repeated X-ray scans detected no liquid in the form of either a film or a mist. This was attributable to the detection limitations of the X-ray image system used. It is possible that very fine droplets of liquid were entrained in the vapor stream. Mass transfer evidence (i.e., deposits) indicated that a thin liquid film extended halfway into the superheater.

## Flow Patterns During Metastable Intervals

Variations were observed in the flow pattern associated with off-design intervals in the loop. These metastable fluctuations became more frequent after several hundred hours of operation with the attendant increasing corrosive attack. When deviations from normal performance occurred, there were distinct changes in the flow pattern at certain locations.

During metastable intervals, there was usually a pronounced cyclic advancing and receding of the liquid film terminal near the boiler exit. The terminal film thickened and repeatedly extended into the superheater (at times, more than halfway toward the superheater exit). This was accompanied by a corresponding cyclic variation in boiler temperatures, boiler pressure drop, and flow rate. The automatic heater power control instruments responded by proportionately varying the boiler power level. This produced interactions that often caused sustained oscillations of flow, pressure, and temperature of the type shown in figure 10(a).

When the previously described perturbations in the liquid film terminal region occurred, the stratified helicoidal flow patterns in the upstream regimes remained unaltered. However, these perturbations seemed to be accompanied by changes in the locus of two-phase inception in the boiler insert zone. This could not be observed clearly because of the mode of construction of the insert zone. However, a cyclic increase and decrease in the thickness of the helical streamlet emerging from the insert zone were apparent. The most distinctly observable overall effect in the boiler consisted of helical wave trains superimposed on the normal flow pattern.
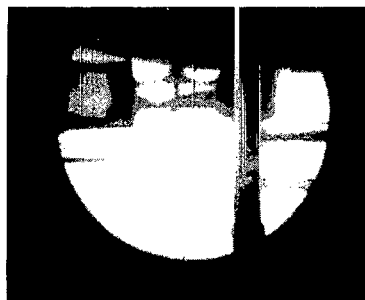
(a) Liquid mercury at low flow rate and room temperature.
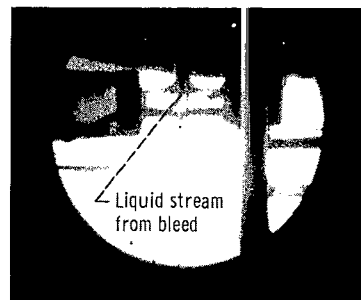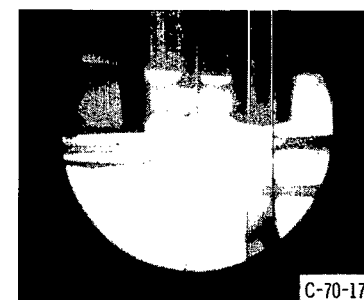
(b) Mercury flash at approximately 1000° F (538° C) in vapor throttle orifice.
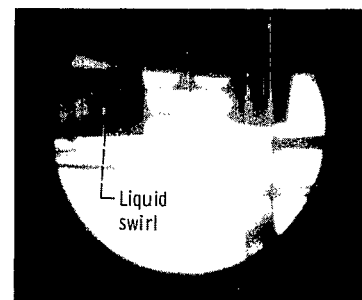
(c) Bulk liquid swirl in condenser inlet.

(d) Throttle under normal operating conditions (no liquid detected).

Figure 15. – Series of X-ray images of flow patterns through vapor throttle under four flow conditions.

There was no visual evidence of a liquid phase of any form (droplets, mist, film, etc.) in the vapor throttle when the boiler operated under normal conditions. However, a dense swirl of liquid mercury always appeared in the vapor throttle exit when low-quality vapor entered the throttle from the superheater. The liquid swirl appeared only in the condenser inlet where there was an abrupt enlargement of the tube diameter. Figure 15 shows mercury flow through the vapor throttle under various conditions. It is considered significant that, during metastable oscillations such as those represented in figure 10, no visual evidence of liquid choking or clogging of the valve was observed. This is considered significant in lieu of conclusions mentioned hereinafter concerning instability effects.

PREVIOUS FLOW PATTERN OBSERVATIONS

A number of previous mercury loops were constructed and operated under flow, temperature, and pressure conditions similar to those of the loop described heretofore. The X-ray system described in the APPARATUS section was used with the previous loops to observe flow patterns. Some of the observations are described briefly in appendix B. The appendix mentions flow phenomena seen in straight-tube boilers in which the problem of liquid carryover was demonstrated. Also described are the prototype helically swaged boiler tubes that demonstrated the improvements obtainable with liquid swirl.

DISCUSSION OF RESULTS

Some aspects of helical liquid motion are discussed first. In a succeeding section flow pattern correlations are discussed with respect to predictability and reproducibility of the patterns described herein. The discussion ends with comments concerning the instability effects and interactions promoted by nucleation and corrosion effects in the boiler inlet region.

Wall Contact and Phase Separation

The object of the groove in the boiler wall was to induce phase separation (i.e., stratification of the liquid phase) by conducting the liquid flow along a continuous helical path. The liquid flow was thus diverted from a purely axial to an essentially circumferential direction. Concomitantly, in this case the area of liquid contact per unit (axial)

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length of the boiler is greater than that for an axially flowing streamlet having the same cross section. These ideas underlie the boiler designs employing twisted metal tapes and wire helix inserts (refs. 2 to 4). The use of helically grooved tubing for improving wall contact and thus heat transfer in heat exchangers and condensers has been previously proposed (refs. 11 to 13).

In the loop described herein, the groove certainly imparted some helical motion to the vapor flowing axially through the boiler-superheater. Therefore, some phase separation probably occurred because of centrifugal separation of liquid droplets that were entrained in the vapor stream. However, it should be expected that a guarantee for good phase separation farther downstream was the initial formation of the helical streamlet in the nucleation zone. When this streamlet has a sufficiently great tangential velocity in the nucleation zone, it tends to persist; but in a boiler, the downstream conditions (e.g., vapor phase velocity) are constantly changing with distance. Therefore, the initial momentum and radial acceleration of the liquid phase are important in ensuring continuance of the helical streamlet (see appendix C).

It was concluded, after a number of prototype mercury boilers were operated, that some sort of swirling device was required throughout the boiler (see appendix B). This requirement applies particularly if the boiler material is one that is not readily wetted by mercury. In this case, it is necessary to force intimate, sustained wall contact to attain wetting and prevent dewetting under two-phase conditions.

Flow Pattern Correlation

The stratified flow patterns that were observed in the mercury boiler can be explained in terms of the Baker flow pattern chart (ref. 14). The chart and an explanation of its usage and terminology are presented in appendix D. It is noteworthy that this chart was derived from adiabatic flow pattern studies. It should be expected that, with heat addition, flow patterns will be influenced by the rate of vapor generation and therefore heat flux. Difficulty in its application to the present case should also be expected because the chart is based on data obtained with straight cylindrical tubes.

The Baker chart for the boiler is shown in figure 16. Loci of G/λ against $L\lambda\psi/G$ are plotted in figure 16 for the insert zone and the remainder of the boiler. The x-scale shows the estimated vapor quality for each value of $L\lambda\psi/G$. (See appendix E for definitions of symbols.)

In the boiler insert region, the diameter of the helical channel was approximately 0.04 inch (1 mm). In the remainder of the boiler and superheater, the hydraulic diameter was bracketed between 0.13 and 0.25 inch (3 and 6 mm). The plots of figure 16 are based on these diameters. The calculations for plotting the loci in the figure did not take
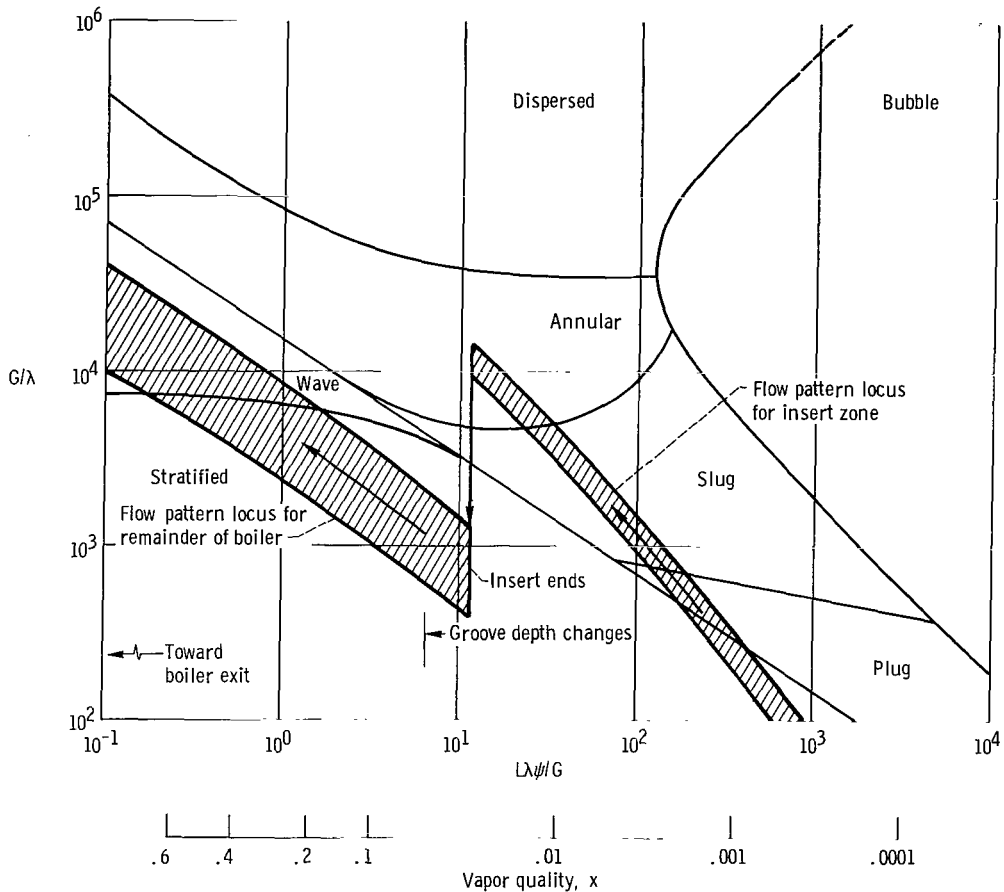
Dispersed

Bubble

Annular

G/λ 10^4

Wave

Flow pattern locus
for insert zone

Stratified

Slug

Flow pattern locus for
remainder of boiler

Insert ends

Groove depth changes

Toward
boiler exit

Plug

10^2
10^{-1} 10^0 10^1 10^2 10^3 10^4

Lλψ/G

.6   .4   .2   .1   .01   .001   .0001

Vapor quality, x

Figure 16. – Predicted flow pattern variations in mercury loop at 1075° F (583° C) with mass flow rate of 78 pounds per hour (9.8x10^{-3} kg/sec).

into account the fact that the liquid flowed on the boiler wall helically instead of axially, as a strict comparison with the Baker chart would require. Nor did the calculation account for the radial acceleration induced by the swirling action.

According to figure 16, a stratified-plug-slug-annular transition is predicted for the insert zone wherein the vapor quality increased from nil to approximately 0.03. Along the insert channel, the predicted variations between stratified and annular were not observed. Because of the strong swirling in the insert region, a radial acceleration several times that of Earth gravity was produced. It is therefore reasonable to expect that stratified flow was stable over a wider range, and thus the transition threshold was raised for stratified flow to higher values of G/λ for a given value of Lλψ/G. Beyond the end of the insert, in the remainder of the boiler, the Baker chart predicts only stratified and wave regimes. The observations showed this to be the case even without corrections for the swirl effects.

The conclusion suggested by the preceding correlation is that the stratified helical

flow was not necessarily unique to the particular boiler described herein. Similar flow patterns can probably be expected for a range of boiler sizes and flow rates by designing in accordance with the Baker equations. However, the applicability of the Baker correlations appeared to depend on the induced liquid-to-wall contact. Previous experience with mercury flowing in straight tubes (appendix B) showed that anomalous flow patterns are more likely to occur with two-phase mercury flow in straight-tube boilers.

Corrosion and Instability Effects

The corrosion and mass transfer in the nucleation zone could account for the increase in metastable fluctuations as the duration of the loop operation increased beyond several hundred hours.

Evidence that nucleation occurred in the insert zone is seen in figure 17, which shows a region downstream of the zone of nucleation inception after exposure to corrosion, erosion, and pitting damage for approximately 1147 hours.

Except for the pitted areas, the insert surface had remained intact, as evidenced by the original tool marks and scratches on its surface. By contrast, the inside surface of the boiler tube had been subject to severe corrosive and erosive attack. It is evident, therefore, that, because of radial acceleration, liquid flowed against the inside surface of the boiler wall. Separation of liquid from the insert surface was enhanced by bubbles

Figure 17. – Boiler insert zone showing corrosion and pitting effects after 1147-hour test.

and/or a vapor blanket that formed as a result of buoyancy effects produced by centrifuging.

The pitting on the insert piece (fig. 17) was probably produced by liquid-entrained vapor bubbles that were formed on the boiler wall and then driven by the liquid stream into the helical crevice formed along the line of contact between the insert cylinder and the boiler wall. The bubbles should have collapsed in this region because the temperature of the insert was less than the temperature of the boiler wall where the bubbles formed (by perhaps 10° F or 5.5° C or more).

It was inferred from the temperature variations near the boiler inlet, that during metastable intervals, the location of the point of two-phase inception was changing. After the loop test ended, examination of the pitting and corrosion patterns in the insert zone seemed to confirm this. Examination of the deposits farther downstream in the boiler showed considerable evidence that granular particles were eroded from the insert zone. This could account for the cavities (i.e., nucleation sites) in the boiler surface in the nucleation zone (ref. 10).

During the first 500 hours of the test, there were only a few moderate metastable intervals. Thereafter, they became more frequent and more pronounced. This increase in metastable oscillations and excursions was apparently related to corrosion and mass removal events in the insert zone. The disturbances were probably triggered by and then interacted with changes in the nucleation pattern. This pattern was, in turn, determined in part by the availability of alternative nucleation sites in the insert zone. As corrosion progressed, more cavities and cracks were formed, and, hence, more alternative nucleation sites became available along the insert zone channel. Meanderings of the point of two-phase inception and changes in the nucleation pattern were probably triggered when these alternative nucleation sites became activated.

Instability Interactions

A comparison of calculated transit times and the period of metastable oscillations indicated that the pulse rate of these oscillations was closely related to the boiler-superheater geometry and heat flux. The amplitude of the metastable pressure oscillations corresponded closely to the pressure drop in the insert zone. This seemed to confirm the conclusion that the oscillations were associated with rhythmic relocations of the point of nucleation inception in the insert zone. This kind of link between oscillations and particulars of boiler geometry and heat flux is discussed by the authors of reference 15. There was no visual evidence indicating that metastable oscillations originated or continued because of liquid choking effects in the vapor throttle. The constancy of pump-developed and output pressure during flow and pressure oscillations seemed to

eliminate the possibility that metastable interactions were transmitted through the liquid leg. Boiler entrance conditions were rather completely decoupled from the condenser because the condenser exit pressure and pressure variations of the liquid condensate column were nearly zero.

Interactions occurring during metastable intervals were probably confined within the boiler-superheater. The X-ray observations indicated that there was a coupling between the nucleation phenomena and the flow patterns seen in the vicinity of the liquid film terminal. The interaction between these two regions was undoubtedly affected by the mode of thermal and power control used for the boiler-superheater.

CONCLUDING REMARKS

The X-ray observations made with prototype mercury boilers indicated that swirling devices greatly enhance phase separation. Without some kind of swirling device, appreciable liquid carryover was found in previous boilers examined by X-ray. In the boiler described herein, shallow helical grooves in the boiler wall served to keep the liquid flowing against the wall. The centrifugal forces thus produced resulted in the intimate, sustained wall contact apparently needed with mercury to induce wetting, prevent dewetting, and thus enhance phase separation.

It appears that good phase separation and prevention of liquid carryover is better accomplished if a helical liquid streamlet with high radial acceleration is produced in the nucleation inception region. The X-ray observations showed that this helical streamlet will persist as an essentially continuous ribbon of liquid if the boiler contains suitable (e.g., helical) surface convolutions.

Flow pattern correlations indicated that the stratified helical flow pattern observed was not necessarily unique to the particular flow conditions and boiler described herein. Similar flow patterns can probably be reproduced for a range of boiler sizes and flow rates. However, anomalous flow patterns are likely with mercury unless there is adequate liquid-to-wall contact (i.e., wetting).

The X-ray observations reported herein were augmented by the corrosion results seen in post-test metallurgical examination of the mercury boiler-superheater. The corrosive attack and deposit patterns added information that enhanced the in situ observations made by the X-ray system.

It was concluded that corrosive attack of the boiler surface and consequent transfer of wall material were responsible for increasing periods of metastable performance after the boiler had operated stably for several hundred hours. Boiling instabilities were probably produced by the formation and activation of alternative nucleation sites in the region of two-phase inception. The corrosion results seem to verify that erosion

figured significantly in triggering changes in the nucleation pattern. The pulse rate of consequent flow and pressure oscillations was related to the transit times associated with the boiler-superheater geometry and heat flux. The transit times and amplitudes of pressure pulses were closely linked with the geometry of the nucleation zone of the boiler inlet.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, January 3, 1970,
            120-27.

APPENDIX A

LOOP CONDITIONING PROCEDURE

Surface contaminants could inhibit mercury wetting and thereby impair performance in the boiler and superheater. A chemical cleaning procedure was used to remove surface contaminants from all loop components. Cleaning was done both before and after fabrication and welding of various components. This ensured that all internal surfaces were free of contaminants detrimental to the experiment and loop performance. All welding was done with an argon purge to ensure against contamination. To ensure against subsequent contamination, the loop was kept under argon backfill and then was charged with triple-distilled mercury under vacuum.

An additional procedure, termed "thermal conditioning," was used to induce mercury wetting in the boiler. The first step in this procedure involved a vacuum pumpdown of the loop and loading of mercury into the loop only after the pressure was less than 10^{-4} torr. Thereafter, the mercury in the boiler was heated to approximately 1100° F $(595^{\circ}$ C). In the boiler, this heating was initially done under zero flow conditions, and when the temperature reached approximately 1100° F $(595^{\circ}$ C), further heating was done with flowing mercury.

Evidence of mercury wetting by this thermal conditioning method was most noticeable in the electromagnetic pump. As explained in reference 16, the developed pressure in the pump was directly related to the degree of wetting. In the boiler, wetting was detected by observing the liquid meniscus as the liquid was withdrawn from the boiler under ambient temperatures. About 2 hours of thermal conditioning were sufficient to secure a significant increase in wetting in the boiler at temperatures between 1050° and 1100° F $(568^{\circ}$ and 595° C).

After initial wetting had been accomplished, the loop could be shut down, cooled to room temperature, and restored to preshutdown conditions within 15 to 20 minutes. This reaffirmed the evidence indicating relatively complete wetting prior to shutdown. Later, when the loop experiment was over, the loop was dissected. Examination of the inside surface of the boiler showed the anticipated effects of wetting.

Only slight dewetting occurred during shutdown in the absence of air leak-in. Previous experience with prototype loops indicated that dewetting would invariably occur whenever the wetted interface was reexposed to the air.

APPENDIX B

FLOW PATTERN OBSERVATIONS IN PREVIOUS MERCURY BOILERS

Boilers Without Helical Swirling Devices

Previous mercury loops were constructed with both straight and slightly curved cylindrical boiler tubes. These loops were operated under approximately the same conditions as the loop described in the text, namely, peak liquid temperature in the boiler inlet, about 1100° F (595° C); maximum superheater temperature, 1300° F (705° C); and mercury flow rate, 100 pounds per hour (12×10^{-3} kg/sec).

With a straight 1/4-inch- (0.63-cm-) diameter tube, X-ray observations showed droplets and sluglets (large, elongated, nonspherical particles) of mercury that were invariably torn away from the main liquid stream. These were swept by the high-velocity vapor into the superheater and into the vapor throttle. Although the boiler tube was slightly inclined from the horizontal, the droplets and sluglets easily skimmed along the boiler surface. When these particles of liquid entered the hotter portions of the superheater, they did not vaporize rapidly but tended to persist both in size and form. This was primarily attributable to the Liedenfrost effect (ref. 17).

In one previous loop formed from a straight cylindrical tube, liquid mercury was seen streaming upward along the entire length of a vertical section of a 1/4-inch- (0.63-cm-) diameter tube comprising the final 2 feet (61 cm) of the superheater. In addition, it was found that liquid carryover occurred even in 1/4-inch- (0.63-cm-) diameter superheater tubes bent on a 4-inch- (10-cm-) diameter helix and with a total length exceeding 10 feet (305 cm).

The previously mentioned boilers confirmed the observation that with mercury there was a strong tendency for liquid particles to become entrained in the vapor. As a result, boiler and superheater performance degenerated appreciably; and wet vapor, often laden with large liquid particles, entered the vapor throttle.

Boilers With Helically Swaged Grooves

One of the prototype loops had a helically grooved boiler tube but contained no insert in the inlet. Another prototype boiler tube was also helically grooved but had a cylindrical insert installed in the inlet. These helically grooved boilers demonstrated how a helical liquid flow pattern can be produced and liquid carryover can be essentially eliminated. The X-ray observations obtained with these boilers are described in the following paragraphs.
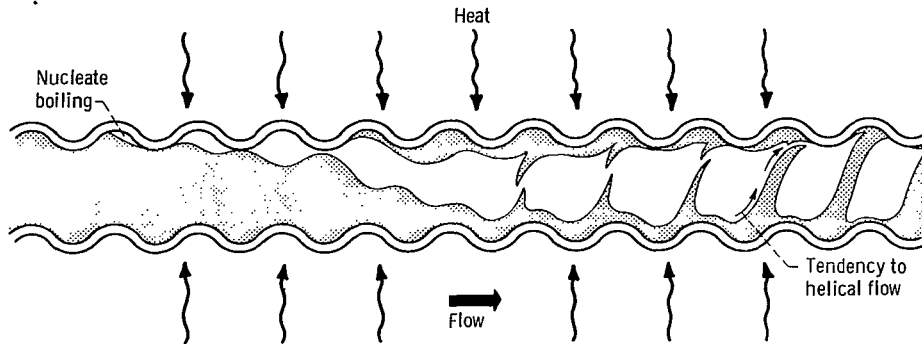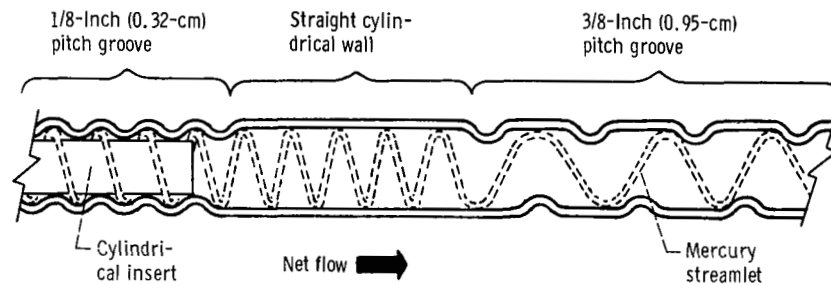
Figure 18. - Representation of inception of two-phase flow in helically swaged boiler tube without insert.

In one previous loop devised by the author, the boiler tube was helically swaged as in figure 6. No insert was used. The inception of two-phase flow began in the manner illustrated in figure 18. The boiler temperature was about 1100° F (595° C). Sufficiently far downstream of the nucleation zone, the liquid flow pattern changed progressively and tended to form a helical streamlet. The flow pattern that finally evolved near the boiler exit resembled the helical streamlet described in the text, but the flow was choppier.
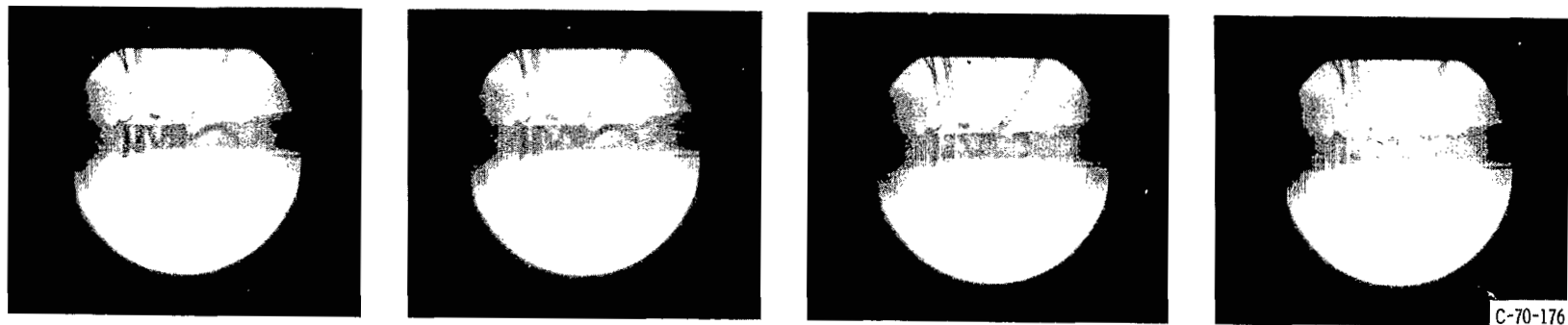
In another prototype, the arrangement shown in figure 19(a) was used. The boiler inlet contained a 1/8-inch- (0.32-cm-) diameter insert cylinder on which the 1/4-inch- (0.64-cm-) diameter by 0.015-inch- (0.038-cm-) wall boiler tube was swaged with a pitch of 1/8 inch (0.32 cm). About 1/4 inch (0.63 cm) downstream of the insert end, a 1-inch (2.5-cm) length of the boiler tube was left unswaged. Beyond this, the tube was again helically grooved but with a pitch of 3/8 inch (0.95 cm).

Figure 19(b) shows a series of X-ray motion picture images of the helical mercury streamlet produced by the configuration just described. The flow rate ranged from 75 to 100 pounds per hour (9.5×10^{-3} to 13×10^{-3} kg/sec), and the temperature in the region shown was approximately 1070° F (577° C). Figure 19(b) shows that the helical streamlet generated in the insert channel persisted even in the ungrooved section. Furthermore, there was a remarkable continuity of the streamlet in transiting the change in groove pitch from 1/8 to 3/8 inch (0.32 to 0.95 cm). Observing the motion picture record of the helical streamlet gives the impression of an extended spring that is axially oscillating slightly.

In both the aforementioned loops, a helical motion was observed. However, in the boiler in which the inlet insert was omitted, a longer boiler length was needed before a helical streamlet tended to appear. In contrast, in the boiler using an insert, the helical streamlet appeared at once and evolved into a smooth helical flow as it progressed through the boiler.

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1/8-Inch (0.32-cm) pitch groove   Straight cylindrical wall   3/8-Inch (0.95-cm) pitch groove

Cylindrical insert

Net flow ➡

Mercury streamlet

(a) Swage and flow patterns near boiler inlet.

C-70-176

(b) X-ray images of helical streamlet flow patterns (note diminishing thickness of helical streamlet from left to right as liquid flow volume decreases).

Figure 19. - Helical streamlet flow pattern in previously investigated mercury loop near boiler inlet demonstrating persistence of pattern generated in insert zone helical flow channel.

APPENDIX C

STABILITY OF HELICAL LIQUID STREAMLET

According to the principle of flow hysteresis, a particular pattern of flow, once produced, tends to persist even if downstream conditions favor a different pattern (refs. 17 and 18). This phenomenon was explored and reaffirmed by X-ray observation in a prototype mercury boiler (see appendix B). In the present case, however, the initial momentum and radial acceleration of the liquid phase were probably most important in ensuring the formation of the helical streamlet. These and the conditions described subsequently were considered essential to the smooth helical flow pattern that was observed in the mercury boiler.

In the boiler of this report, a helical streamlet was formed in the single-phase, liquid portion of the insert zone channel. Beyond the end of the insert, the continuity of the helical flow depended on the momentum of the liquid, the continuity of the groove in which the liquid flowed, and the high cohesiveness (surface tension) of the mercury. To acquire sufficient momentum, the liquid streamlet had to be accelerated. This was accomplished in the insert zone. As more vapor was generated, both the liquid and vapor velocity increased concomitantly. The estimated tangential velocity of the liquid streamlet at the end of the insert was about 8 feet per second (240 cm/sec).

An estimate of the minimum tangential velocity needed to overcome the effect of gravity is given by

$$v = 2\pi \sqrt{gr}$$

where v is the tangential velocity, g is the acceleration due to gravity, and r is the tangential radius of the groove. In the present case, a velocity of approximately 3.2 feet per second (98 cm/sec) was calculated. This velocity is the minimum needed until wetting takes place. Thereafter, surface tension forces (wetting) supplement the centrifugal forces, thus keeping the liquid on the wall.

As the liquid streamlet progressed along the boiler, its tangential velocity diminished. At the end of the boiler, in the liquid film terminal region, analysis of the motion picture records showed the screw-like tangential velocity to be about 1 foot per second (30 cm/sec). This indicated the extent to which surface tension forces (i.e., adhesion to the wall) were important in overcoming gravity (because 1 ft/sec or 30 cm/sec is significantly less than the 3.2 ft/sec or 98 cm/sec required according to the preceding equation).

APPENDIX D

FLOW PATTERN PREDICTION CHART

A representation of flow regimes produced by concurrent flow of liquid and gas was obtained from a systematic study by the author of reference 14. This representation is referred to as the Baker flow pattern prediction chart. The chart is reproduced in figure 20 and pertains to adiabatic flow (without heat addition) in cylindrical horizontal tubes. (All symbols are defined in appendix E.) The flow pattern terminology used in figure 20 is defined to avoid possible ambiguity. (The definitions are from ref. 19.)

(1) Bubble: The liquid phase is connected, and the gas flows in the form of bubbles.

(2) Plug: As the gas flow rate increases, the bubbles coalesce, and plugs of liquid and gas flow alternately along the top of the tube.
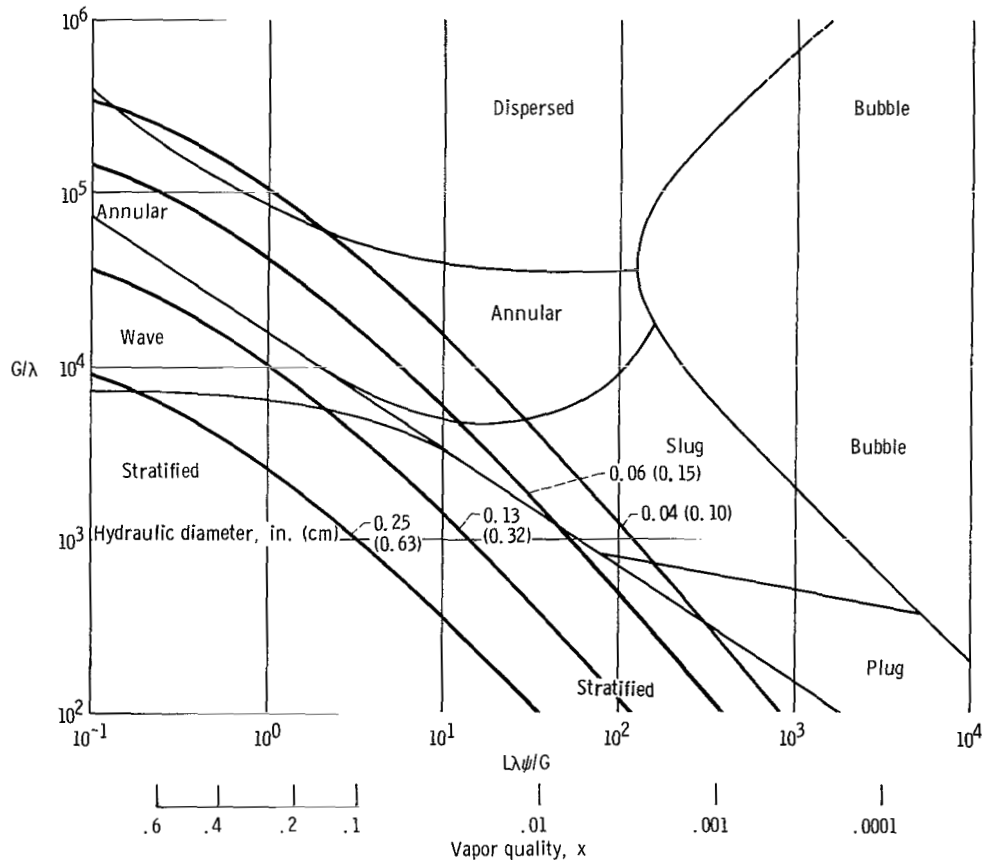

Figure 20. - Baker flow pattern prediction chart with predicted flow pattern variations for tubes of four different diameters. Temperature, 1075° F (583° C); mass flow rate, 78 pounds per hour (9.8x10^{-3} kg/sec).

(3) Stratified: Liquid flows along the bottom of the pipe and gas flows above. The gas-liquid interface remains smooth, and the hydraulic area fraction occupied by each phase remains constant.

(4) Wave: As the gas rate is increased in stratified flow, surface waves are produced with increasing amplitude.

(5) Slug (or high-amplitude wave): As the gas flow rate is increased further, the liquid wave amplitude increases to a magnitude where it touches the top of the pipe.

(6) Annular: The liquid flows as a film of varying thickness on the wall of the pipe, while gas flows axially as a high-speed core through the center. There is almost inevitably some liquid carried in dispersed or atomized form by the vapor.

(7) Dispersed: Dispersed, fog, and mist flows are classified as a separate flow regime in which the liquid phase appears as a fine entrainment in vapor or gas, and the annular film is totally absent.

Superimposed on the Baker chart of figure 20 are four curves, each representing a straight cylindrical tube with a different diameter, namely, 0.04 inch (0.10 cm), 0.06 inch (0.16 cm), 0.13 inch (0.32 cm), and 0.25 inch (0.63 cm). The superimposed curves are plots of the parameter G/λ against $L\lambda\psi/G$ for concurrent mercury liquid-vapor flow of 78 pounds per hour (9.8×10^{-3} kg/sec) at a temperature of 1075° F (580° C). The vapor quality corresponding to various values of $L\lambda\psi/G$ may be read from the x-abscissa of figure 20.

The progression of patterns for each tube size is read right to left. For example, for the 0.06-inch- (0.16-cm-) diameter tube, the plot of figure 20 predicts a progression in flow patterns from stratified to slug to annular as the vapor quality increases with downstream distance from 0.001 to 0.6. For the 0.13-inch- (0.32-cm-) diameter tube, the pattern should vary from stratified to wave. It should be remembered that the lines of the Baker plot do not represent sharp boundaries but instead show general areas where probable transitions occur.

APPENDIX E

SYMBOLS

G   mass velocity of gas or vapor phase, based on total cross-sectional area of pipe in Baker chart, $kg/(m^2)(sec)$; $lbm/(ft^2)(hr)$

g   acceleration due to gravity, $9.80 \ m/sec^2$; $32.2 \ ft/sec^2$

L   mass velocity of liquid phase, based on total cross-sectional area of pipe in Baker chart, $kg/(m^2)(sec)$; $lbm/(ft^2)(hr)$

r   inside radius of boiler tube (max), m; ft

v   velocity of liquid phase, m/sec; ft/sec

x   fraction representing local mass flow of vapor with respect to total mass flow

λ Baker parameter (ref. 14), $(\rho_g/0.075)(\rho_l/62.3)$

μ_l viscosity of liquid, $(N)(sec)/m^2$; cP in eq. for ψ

ρ_g density of gas or vapor, kg/m^3; lb/ft^3 in eq. for λ

ρ_l density of liquid, kg/m^3; lb/ft^3 in eqs. for λ and ψ

σ surface tension between liquid and gas, N/m; dynes/cm in eq. for ψ

ψ Baker parameter (ref. 14), $(73/\sigma)\left[\mu_l (62.3/\rho_l)^2\right]^{1/3}$

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